QCD analysis of polarized inclusive and semi-inclusive DIS data

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Abstract

A new combined NLO QCD analysis of the polarized inclusive and semi-inclusive DIS data is presented. In contrast to previous combined analyses, the $1/Q^2$ terms (kinematic - target mass corrections, and dynamic - higher twist corrections) in the expression for the nucleon spin structure function g_1 are taken into account. The new COMPASS data are included in the analysis. The impact of the semi-inclusive (SIDIS) data on the polarized parton densities (PDFs) and on the higher twist corrections is demonstrated. The controversial behavior of the polarized strange quark density obtained from the fit to the DIS data alone, and a combined analysis of DIS and SIDIS data is discussed.

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1 Introduction

Experiments on polarized inclusive deep inelastic lepton-hadron scattering (DIS), reactions of the type $l + p \to l' + X$ with both polarized lepton and hadron, because of the non-existence of neutrino data, can only, in principle yield information on the sum of quark and antiquark parton densities i.e. information on the polarized densities $\Delta u + \Delta\bar{u}$, $\Delta d + \Delta\bar{d}$, $\Delta s + \Delta\bar{s}$ and ΔG.

Information about the antiquark densities $\Delta\bar{u}, \Delta\bar{d}$ and the separate Δs and $\Delta\bar{s}$ strange densities thus has to be extracted from other reactions, notably polarized semi-inclusive lepton-hadron reactions (SIDIS) $l + p \to l' + h + X$, where h is a detected hadron in the final state, or from semi-inclusive hadronic scattering (SIHS) like $p + p \to h + X$, involving polarized protons, and only possible at the RHIC collider at Brookhaven National Laboratory.

In contrast to the situation in unpolarized DIS, a large portion of the most accurate data on polarized DIS lie in a kinematical region where Target Mass Corrections (TMC) of order M^2/Q^2 (whose form is exactly known), and dynamical Higher Twist (HT) corrections of order Λ^2_{QCD}/Q^2 are important [1, 2]. We have thus included such terms in our description of the DIS data. However, for the SIDIS data, we do not know the analogous results at present, so do not include such terms. As it happens almost all the SIDIS data we utilize are in kinematic regions where such corrections should not be important.

In this talk we present the results of our combined NLO QCD analysis of polarized inclusive and semi-inclusive DIS data [3]. The new COMPASS data [4–6] are also included in the fit. In the calculations of the semi-inclusive asymmetries $A^h_{1N}(x, z, Q^2)$, the NLO MRST'02 PDFs [7] and the NLO DSS fragmentation functions (FFs) [8] were used for the unpolarized parton densities and the fragmentation functions, respectively. The new results for the polarized PDFs are compared to both the LSS'06 PDFs [1], obtained from the fit to the inclusive DIS data alone, and to those obtained from the first global analysis performed by DSSV group [9].

2 Results of analysis

In this Section we present the numerical results of our global NLO QCD fit to the world inclusive and semi-inclusive DIS data (for references to the

data sets see our paper [3]). The data used (841 experimental points for DIS and 202 experimental points for SIDIS) cover the following kinematic regions: $\{0.005 \leq x \leq 0.75,\ 1 < Q^2 \leq 62\, GeV^2\}$ for DIS and $\{0.005 \leq x \leq 0.48,\ 1 < Q^2 \leq 60\, GeV^2\}$ for SIDIS processes. The statistical and systematic errors are added in quadrature and the uncertainties of the polarized PDFs presented correspond to $\Delta\chi^2 = 1$. A good description of the data is achieved for both the inclusive (χ^2_{NrP}=0.85) and semi-inclusive (χ^2_{NrP}=0.90) processes (NrP is the number of corresponding experimental points). The total value of χ^2_{DF} is 0.88. The quality of the fit to the data is demonstrated in Fig. 1 in [3].

2.1 The role of semi-inclusive DIS data in determining the polarized sea quark densities: Controversy about strange quark polarization

Due to SIDIS data a flavor decomposition of the polarized sea is achieved and the light anti-quark polarized densities $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$ are determined without any additional assumptions. While $\Delta\bar{d}(x)$ is negative for any x in the measured x region, $\Delta\bar{u}(x)$ is a positive, passes zero around $x = 0.2$ and becomes negative for large x. Sign-changing solutions are also found for the polarized strange sea $\Delta\bar{s}(x)$ and gluon $\Delta G(x)$ densities. The sign-changing behavior for $\Delta G(x)$ is not surprising since it was already found from the analysis of the inclusive DIS data alone [1]. On the other hand, on the basis of results from all published analyses of inclusive DIS, we consider the sign-changing solution for $\Delta\bar{s}(x)$ quite puzzling. The central values of the sea quark and gluon polarized densities together with their error bands are presented and compared to those of DSSV (dashed curves) in Fig. 1.

Our LSS'06 PDFs (dot curves) [1] obtained from the NLO QCD analysis of the world inclusive DIS data are also presented in Fig. 1. While the light anti-quark polarized densities $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$ cannot be, in principle, determined from polarized inclusive DIS data, the sum $(\Delta s + \Delta\bar{s})(x, Q^2)$ *is* well determined and all the NLO QCD analyses yield for this sum a *negative* value for any x in the measured region (for example, see Refs. [1, 10]). In these analyses, however, a term like $(1 + \gamma x)$, which would permit a sign-change, was not included in the input parametrization of $(\Delta s + \Delta\bar{s})(x, Q_0^2)/2$. We therefore re-analysed the world polarized inclusive DIS data using such a term in the input strange sea quark density

$$x(\Delta s + \Delta\bar{s})(x, Q_0^2)/2 = Ax^{\alpha}(1 - x)^{\beta}(1 + \gamma x). \qquad (1)$$

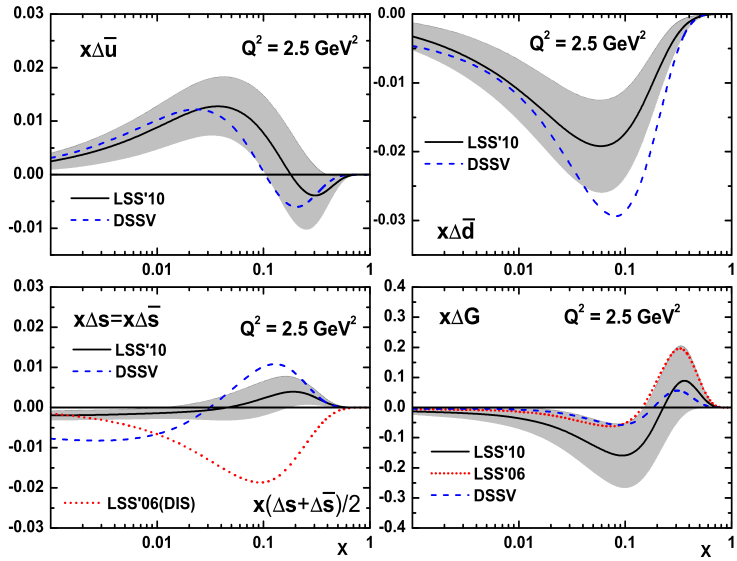

Figure 1. Our NLO sea quarks and gluon polarized PDFs at $Q^2 = 2.5\ GeV^2$ in the $\overline{\mathrm{MS}}$ scheme. For comparison the DSSV PDFs [9] are also presented.

Our preliminary results confirm the previous ones, namely, that $(\Delta s + \Delta\bar{s})(x, Q^2)/2$ is negative in the measured (x, Q^2) region. So, the behaviour of the polarized strange quark density remains controversial. Note that in the presence of SIDIS data Δs and $\Delta\bar{s}$ can, in principle, be separately determined, as was done recently by the COMPASS Collaboration, where it was shown [11] that there is no significant difference between $\Delta s(x)$ and $\Delta\bar{s}(x)$ in the x-range covered by their inclusive and semi-inclusive DIS data. However, the errors of the extracted values of the difference $x(\Delta s(x) - \Delta\bar{s}(x))$ are rather large to allow us to conclude that the assumption $\Delta s(x) = \Delta\bar{s}(x)$ used in our's and the DSSV analyses is correct. So, if it is not correct, it might possibly be the cause that $(\Delta s + \Delta\bar{s})(x, Q^2)/2$ densities obtained from the analyses of inclusive DIS data and combined inclusive and semi-inclusive DIS data sets, respectively, are in contradiction. However, at first glance, it looks as if the difference between Δs and $\Delta\bar{s}$ would have to be quite significant and might contradict the COMPASS results. Perhaps a more important issue is the sensitivity of the results to the form of the fragmentation functions. An

analysis by the COMPASS group [5] demonstrated that the determination of $\Delta\bar{s}(x)$ strongly depends on the set of the fragmentation functions used in the analysis and that the DSS FFs are crucially responsible for the unexpected behavior of $\Delta\bar{s}(x)$ obtained from the combined analysis.

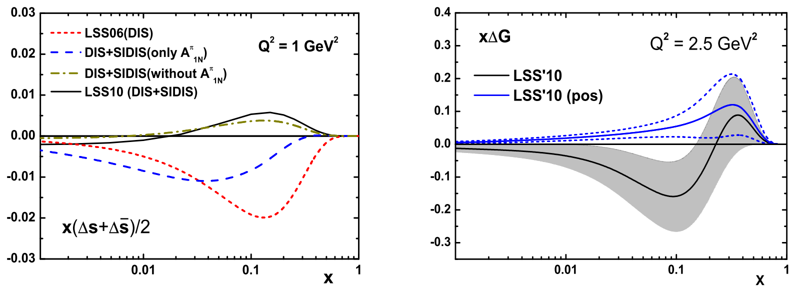

Figure 2. Dependence of the form of the polarized strange quark density on different fits (**left**). Comparison between the positive and sign-changing gluon densities (**right**).

In order to understand better the issue of the sign-changing behavior of $\Delta\bar{s}(x)$ in the case of the combined fit to the inclusive DIS and SIDIS data a more detailed analysis has been done. In this analysis the very recent COMPASS data on the asymmetries $A_{1,p}^{\pi+(-)}$, $A_{1,p}^{K+(-)}$ for charged pions and kaons produced on a proton target [11] have been included. First, we have performed a fit to the DIS and SIDIS data including *only* the data on the pion A_{1N}^{π} asymmetries. Note that in this case only the sum $x(\Delta s+\Delta\bar{s})(x,Q_0^2)$ can be determined from the data because of the reasonable assumption $D_s^{\pi}=D_{\bar{s}}^{\pi}$ used for all the sets of the fragmentation functions. Second, we fitted the inclusive DIS and SIDIS data *excluding* the data on the pion A_{1N}^{π} asymmetries. The results on $x(\Delta s+\Delta\bar{s})/2$ are illustrated in Fig. 2 (left) and compared to those obtained from DIS (dot curve) and the combined DIS and SIDIS (solid curve) analyses. Note that for the fragmentation functions the DSS set was used. As seen from Fig. 2 (left), in the presence only of the A_{1N}^{π} data $x(\Delta s+\Delta\bar{s})/2$ (dashed curve) is still negative in the measured x region. The exclusion of these data from the full set of SIDIS data leads to a sign-changing behavior of $x(\Delta s+\Delta\bar{s})/2$ (dash dot curve). Note that in the later case the assumption $\Delta s(x)=\Delta\bar{s}(x)$ is used because the accuracy of the present SIDIS data is not enough to separate the strange quark and

anti-quark polarized densities. One can conclude from this study that the main reason $\Delta\bar{s}(x)$ to change a sign are the kaon data and the kaon FFs which are less known and very different for the different sets of fragmentation functions. So, the study of the sensitivity of $\Delta\bar{s}(x)$ to the different kaon FFs used in the analysis is one of the key points we plan to investigate in the future.

In Fig. 3 we present our results for the polarized $\Delta u(x)$ and $\Delta d(x)$ densities at $Q^2 = 2.5\ GeV^2$, which are consistent with those obtained by DSSV (dashed blue curves). As expected, the SIDIS data do not influence essentially the sums $(\Delta u(x) + \Delta\bar{u}(x))$ and $(\Delta d(x) + \Delta\bar{d}(x))$ already well determined from the analysis of the inclusive DIS data. This fact is illustrated in Fig. 2 where our results from the combined analysis are compared with our LSS'06 PDFs.

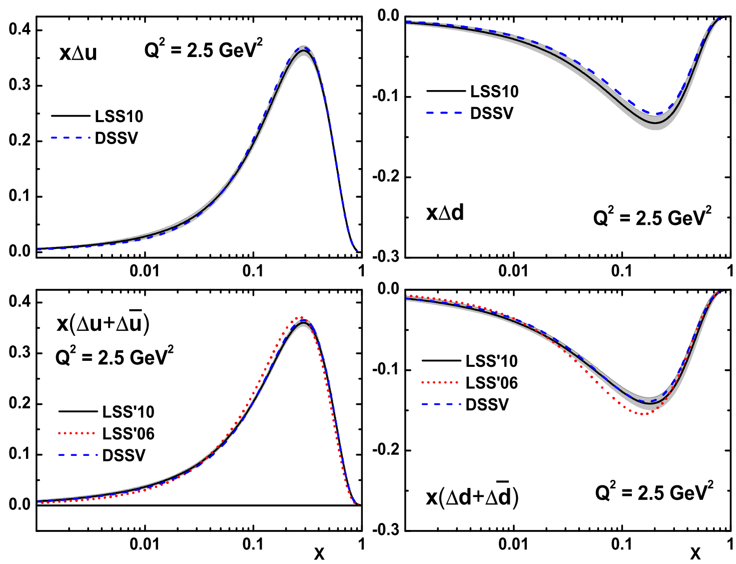

Figure 3. Our NLO Δu, Δd, $(\Delta u + \Delta\bar{u})$ and $(\Delta d + \Delta\bar{d})$ polarized parton densities at $Q^2 = 2.5\ GeV^2$. DSSV [9] as well as LSS'06 [1] results for the corresponding densities are presented too.

2.2 The sign of gluon polarization

We have found that the combined NLO QCD analysis of the present polarized inclusive DIS and SIDIS data cannot rule out the solution with a positive gluon polarization. The values of χ^2/DF corresponding to the fits with sign-changing $x\Delta G(x,Q^2)$ and positive $x\Delta G(x,Q^2)$ are practically the same: $\chi^2/DF(\text{node } x\Delta G) = 0.883$ and $\chi^2/DF(x\Delta G > 0) = 0.888$, and the data cannot distinguish between these two solutions (see Fig. 2 (right)). The sea quark densities obtained in the fits with positive and sign-changing $x\Delta G(x)$ are almost identical. Note that the extracted HT values corresponding to both fits are also effectively identical. As a result, one can conclude that including the SIDIS data in the QCD analysis does not help to constrain better the polarized gluon density.

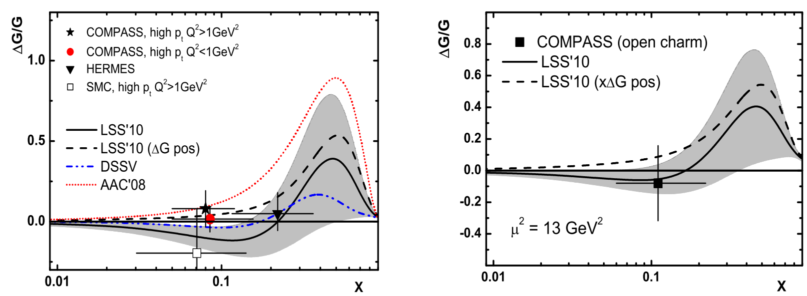

Figure 4. Comparison between the experimental data and NLO($\overline{\text{MS}}$) curves for the ratio $\Delta G(x)/G(x)$ at $Q^2 = 3$ GeV^2 (**left** - high p_t pairs) and $Q^2 = 13$ GeV^2 (**right** - open charm) corresponding to positive and sign-changing $x\Delta G$. Error bars represent the total (statistical and systematic) errors. The horizontal bar on each point shows the x-range of the measurement. The NLO DSSV [9] and AAC (the last Ref. in [10]) curves on $\Delta G(x)/G(x)$ are also presented.

In Fig. 4 the ratio $\Delta G(x)/G(x)$ calculated for both the sign-changing and positive solutions for $\Delta G(x)$ obtained in our NLO QCD analysis is compared with the directly measured values of $\Delta G/G$ obtained from a quasi-real photoproduction of high p_t hadron pairs [12–14], and from the open charm production [15] measurements. For the unpolarized gluon density $G(x)$ in the ratio above we have used that of the NLO MRST'02 [7]. The theoretical curves are given for $\mu^2 = 3$ GeV^2 (high p_t hadron pairs) and $\mu^2 = 13$ GeV^2 (open charm). As seen from Fig. 4, both solutions for the polarized gluon

density are well consistent with the experimental values of $\Delta G/G$. It should be noted, however, that in the extraction of $\Delta G/G$ by the experiments a LO QCD treatment has been used. A NLO extraction of the measured values is needed in order for this comparison to be quite correct. In conclusion, the magnitude of the gluon density $x\Delta G(x)$ obtained from our combined NLO QCD analysis of inclusive and semi-inclusive DIS data and independently, from the photon-gluon fusion processes, is small in the region $x \simeq 0.08 - 0.2$.

When our combined analysis was finished, the COMPASS Collaboration reported the first data on the asymmetries $A_{1,p}^{\pi_{+(-)}}$, $A_{1,p}^{K_{+(-)}}$ for charged pions and kaons produced on a proton target [11]. As seen in Fig. 5, our predictions for these asymmetries are in a very good agreement with the data at measured x and Q^2.

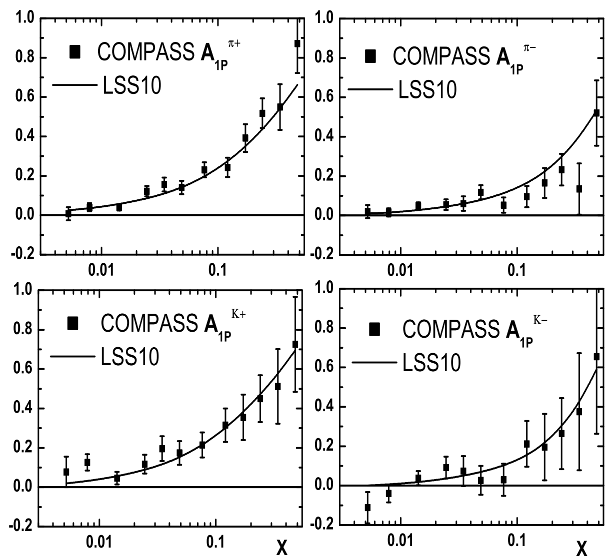

Figure 5. Our predictions for the COMPASS asymmetries for charged pions and kaons produced on a proton target.

2.3 High twist effects

In contrast to other combined analyses of the inclusive and semi-inclusive DIS data, we take into account the target mass and higher twist corrections in a the DIS sector. The values of the HT corrections to g_1 extracted from the data in this analysis are shown in Fig. 6. Compared to the HT(LSS'06) corrections obtained in our analysis of the inclusive DIS data alone [1] the values of the HT corrections for the proton target are practically not changed, while the central values of HT corrections for the neutron target are smaller in the region $x < 0.2$, but in agreement with $\mathrm{HT}^{(\mathrm{n})}$(LSS'06) within the errors, excepting the x region around $x = 0.1$ We consider the tendency of the $\mathrm{HT}^{(\mathrm{n})}$ corrections to be smaller in the region $x < 0.2$ to be a result of the new behavior of $\Delta s(x)$ i.e. positive for $x > 0.03$. The positive contribution in g_1^n from $\Delta s(x)$ should be compensated by a less positive $\mathrm{HT}^{(\mathrm{n})}$ contribution in this region. Since the biggest difference between the values of $\Delta s(x)_{(\mathrm{DIS+SIDIS})}$ and $\Delta s(x)_{\mathrm{DIS}}$ is in the region $x \sim 0.1$ (see Fig. 1) this effect is biggest in this x region. The impact of $\Delta s(x)$ on HT corrections is visible mainly for the neutron target because the contribution of $\Delta s(x)$ in g_1^n is relatively larger than that in g_1^p.

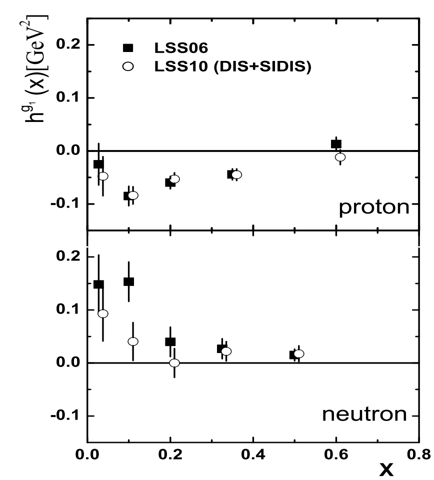

Figure 6. Impact of SIDIS data on HT effects for proton and neutron targets.

Note that our results on the HT corrections to the nucleon spin structure function $g_1(x, Q^2)$ are in a good agreement with the phenomenological

study of their first moments [16, 17], as well as with the QCD sum rule estimates [18], the large N_c limit in QCD [19] and the instanton model [19, 20] predictions.

2.4 The spin sum rule

Let us finally discuss the present status of the proton spin sum rule. Using the values for $\Delta\Sigma(Q^2)$ and $\Delta G(Q^2)$ at $Q^2 = 4\ GeV^2$, the first moments of the quark singlet $\Delta\Sigma(x, Q^2)$ and gluon $\Delta G(x, Q^2)$ densities, obtained in our analysis one finds for the spin of the proton:

$$\begin{aligned} J_z = \frac{1}{2} &= \frac{1}{2}\Delta\Sigma(Q^2) + \Delta G(Q^2) + L_z(Q^2) \\ &= -0.21 \pm 0.46 + L_z(Q^2) \ \ (\text{node } \Delta G), \\ &= \ \ 0.42 \pm 0.19 + L_z(Q^2) \ \ (\text{pos } \Delta G). \end{aligned} \tag{2}$$

In Eq. (2) $L_z(Q^2)$ is the sum of the angular orbital momenta of the quarks and gluons. Although the central values of the quark-gluon contribution in (2) are very different in the two cases, in view of the large uncertainty coming mainly from the gluons, one cannot yet come to a definite conclusion about the contribution of the orbital angular momentum to the total spin of the proton.

3 Summary

A new combined NLO QCD analysis of the polarized inclusive and semi-inclusive DIS data is presented. In contrast to previous combined analyses, the $1/Q^2$ terms (kinematic - target mass corrections, and dynamic - higher twist corrections) to the nucleon spin structure function g_1 are taken into account. The new results for the PDFs are compared to both the LSS'06 PDFs obtained from a fit to the inclusive DIS data alone, and to those obtained from the DSSV global analysis. The role of the semi-inclusive data in determining the polarized sea quarks is discussed. Due to SIDIS data $\Delta\bar{u}(x, Q^2)$ and $\Delta\bar{d}(x, Q^2)$, as well $\Delta u(x, Q^2)$ and $\Delta d(x, Q^2)$ are determined without additional assumptions about the light sea quarks. The SIDIS data, analysed under the assumption $\Delta s(x, Q^2) = \Delta\bar{s}(x, Q^2)$, imposes a sign-changing $\Delta\bar{s}(x, Q^2)$, as in the DSSV analysis, but our values are smaller in magnitude, less negative at $x < 0.03$ and less positive for $x > 0.03$. Note that

$\Delta\bar{s}(x,Q^2)_{\rm SIDIS}$ differs essentially from the negative $\frac{1}{2}(\Delta s + \Delta\bar{s})(x,Q^2)_{\rm DIS}$ obtained from all the QCD analyses of inclusive DIS data. It was also shown that when in the combined QCD analysis only the pion SIDIS data are included the polarized strange quark density is still negative for any x in the measured region, and the change-signing behavior of $\Delta\bar{s}(x,Q^2)$ is due to the kaon asymmetries calculated by the DSS fragmentation functions. A further detailed analysis of the sensitivity of $\Delta\bar{s}(x,Q^2)$ to the kaon FFs is needed, and any model independent constraints on FFs would help. Another possible reason for this disagreement could be the assumption $\Delta s(x,Q_0^2) = \Delta\bar{s}(x,Q_0^2)$ made in the global analyses. However, this would probably require a significant difference between Δs and $\Delta\bar{s}$, which is not seen in the COMPASS analysis. In any case, obtaining a final and unequivocal result for $\Delta\bar{s}(x)$ remains a challenge for further research on the internal spin structure of the nucleon.

We have found also that the polarized gluon density is still ambiguous, and the present polarized DIS and SIDIS data cannot distinguish between the positive and a sign-changing gluon densities $\Delta G(x)$. This ambiguity is the main reason that the quark-gluon contribution into the total spin of the proton is still not well determined.

Finally, our combined NLO QCD analysis confirms our previous results on the higher twist corrections to the nucleon spin structure function g_1^N, namely, that they are not negligible in the pre-asymptotic region and have to be accounted for in order to extract correctly the polarized PDFs.

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References

[1] E. Leader, A.V. Sidorov, D.B. Stamenov, Phys. Rev. **D75**, (2007) 074027.

[2] E. Leader, A.V. Sidorov, D.B. Stamenov, Phys. Rev. D **80**, (2009) 054026.

[3] E. Leader, A. V. Sidorov, D. B. Stamenov, Phys. Rev. **D82**, (2010) 114018.

[4] M. G. Alekseev et al. (COMPASS Collaboration), Phys. Lett. B **660**, (2008) 458.

[5] M. G. Alekseev et al. (COMPASS Collaboration), Phys. Lett. **B680**, (2009) 217.

[6] M. G. Alekseev et al. (COMPASS Collaboration), Phys. Lett. **B690**, (2010) 466.

[7] A.D. Martin, R.G. Roberts, W.J. Stirling, R.S. Thorne, Eur. Phys. J. **C28**, (2003) 455.

[8] D. de Florian, R. Sassot, and M. Stratmann, Phys. Rev. D **75**, (2007) 114010; Phys. Rev. D **76**, (2007) 074033.

[9] D. de Florian, R. Sassot, M. Stratmann, W. Vogelsang, Phys. Rev. **D80**, (2009) 034030.

[10] M. Glück, E. Reya, M. Stratmann, W. Vogelsang, Phys. Rev. **D63**, (2001) 094005; J. Blumlein and H. Bottcher, Nucl. Phys. **B636**, (2002) 225; V. Y. Alexakhin et al. (COMPASS Collaboration), Phys. Lett. **B647**, (2007) 8; M. Hirai and S. Kumano, Nucl. Phys. **B813**, (2009) 106.

[11] M. G. Alekseev et al. (COMPASS Collaboration), Phys. Lett. **B693**, (2010) 227.

[12] B. Adeva *et al.* (Spin Muon Collaboration), Phys. Rev. D **70**, (2004) 012002.

[13] S. Procureur (for the COMPASS Collaboration), in *Proceedings of 41st Rencontres de Moriond on QCD and high Energy Hadronic interactions, La Thuile, Aosta Valley, Italy, 18-25 Mar 2006*, edited by Etienne Auge and Jean Tran Thanh Van (Gioi publishers, Hanoi, Vietnam, 2006); M. Stolarski (COMPASS Collaboration), in *Proceedings of 16th International Workshop on Deep Inelastic Scattering and Related Subjects (DIS2008), 7-11April, 2008, London, UK*, edited by R. Devenish and J. Ferrando (Science Wise Publishing, 2008, 209) [http://www.sciwipub.com/index.php?doit=dis2008].

[14] A. Airapetian et al. (HERMES Collaboration), arXiv:1002.3921 [hep-ex].

[15] C. Franco (on behalf of the COMPASS Collaboration), talk given at the XVIII International Workshop on Deep Inelastic Scattering and Related Subjects, Florence, April 19 - 23, 2010.

[16] A. Deur *et al.*, Phys. Rev. D **78**, (2008) 032001.

[17] R.S. Pasechnik, D.V. Shirkov, and O.V. Teryaev, Phys. Rev. D **78**, (2008) 071902; R.S. Pasechnik *et al.*, Phys. Rev. D **81**, (2010) 016010.

[18] I.I. Balitsky, V.M. Braun, and A.V. Kolesnichenko, Phys. Lett. B **242**, (1990) 245, Erratum *ibid* B **318**, (1993) 648; E. Stein *et al.*, Phys. Lett. B **353**, (1995) 107.

[19] J. Balla, M.V. Polyakov, and C. Weiss, Nucl. Phys. **B510**, (1998) 327.

[20] A.V. Sidorov and C. Weiss, Phys. Rev. D **73**, (2006) 074016.